

Enabling Spacecraft Formation Flying through Position Determination, Control and Enhanced Automation Technologies

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ABSTRACT - Formation Flying is revolutionizing the way the space community conducts science missions around the Earth and in deep space. This technological revolution will provide new, innovative ways for the community to gather scientific information, share that information between space vehicles and the ground, and expedite the human exploration of space. Once fully matured, formation flying will result in numerous sciencecraft acting as virtual platforms and sensor webs, gathering significantly more and better science data than can be collected today. To achieve this goal, key technologies must be developed including those that address the following basic questions posed by the spacecraft:

Where am I?

Where is the rest of the fleet?

Where do I need to be?

What do I have to do (and what am I able to do) to get there?

The answers to these questions and the means to implement those answers will depend on the specific mission needs and formation configuration. However, certain critical technologies are common to most formations. These technologies include high-precision position and relative-position knowledge including Global Positioning System (GPS) and celestial navigation; high degrees of spacecraft autonomy; inter-spacecraft communication capabilities; targeting and control including distributed control algorithms, and high-precision control thrusters and actuators.

This paper provides an overview of a selection of the current activities NASA/DoD/Industry/Academia are working to develop Formation Flying technologies as quickly as possible, the hurdles that need to be overcome to achieve our formation flying vision, and the team's approach to transfer this technology to space. It will also describe several of the formation flying testbeds, such as Orion and University Nanosatellites, that are being developed to demonstrate and validate many of these innovative sensing and formation control technologies.

1-INTRODUCTION

Earth and space scientists are just beginning to understand the full potential of space vehicle formation flying. In a few short years, this technology, once considered a high-risk oddity by the space community, has now become fully embraced by Earth and space scientists around the world. Just prior to the selection of the New Millennium Program (NMP) Earth Observing-1 (EO-1) mission in 1996—the first autonomous formation flying Earth science mission—there were only one or two formation flying concepts being considered by NASA. This has changed dramatically. Table 1 depicts many of the Earth and space mission concepts currently being considered by NASA and the Air Force Research Laboratory (AFRL). Clearly, the substantial benefits gleaned from obtaining simultaneous measurements from numerous co-flying vehicles and sensor webs have resulted in a virtual explosion of future Earth and space science distributed spacecraft mission concepts.

A simple analogy can be used to illustrate the fundamental change that occurs in Earth and space science when formation flying is employed. The analogy used is the observation of a hurricane as it develops off the coast of the United States from two different perspectives. The Earth and space science measurements performed today are comparable to viewing snapshots or stills at a very slow rate of the storm as it develops. Using formation flying technology, the visual perspective and understanding will be radically changed. In the hurricane example, this would be analogous to watching a live video feed of the storm game using many fixed and movable cameras. For the scientists, this new perspective should provide a unique "birds eye view" of the Earth, the universe, and the changing dynamics up to the moment. Thus providing spatio-temporal knowledge.

The current complement of Earth Science missions perform infrequent measurements of targeted areas of the Earth using very large, expensive spacecraft platforms (e.g. Landsat-7 which takes 16 days to retrace its ground swath). In the future, swarms of inexpensive miniature space vehicles or spacecraft, flying in formations or "webs", will replace these expensive space platforms. These formations and webs will provide continuous measurements of the processes and events effecting the Earth. Space science will also be significantly impacted by formation flying technology. For example, the space science community's ability to understand the events and processes that occur between the Sun and the Earth (the so called Sun-Earth connection) is limited to a just a few spacecraft in various Earth and Heliocentric orbits. A significant improvement in the understanding of the dynamics of the magnetosphere can be accomplished if an armada of miniature science probes flying around the Earth and Sun in a loose formation replaces these spacecraft. Significant improvements in space-based interferometry can be accomplished by flying several spacecraft in a tight formation, increasing the baseline and number of instruments comprising the system and eliminating the restrictions imposed by the use of physical structures to establish, maintain and control instrument separation and stability. As shown, the benefits of formation flying propagate throughout the entire agency Space Science Enterprises—Origins, Sun-Earth Connection, Structure and Evolution of the Universe, and Solar System Exploration.

Formation flying will also change the way NASA and the space community conducts Human Exploration and Development of Space. In the future, autonomous Space Shuttle and Space Station rendezvous and docking using enhanced GPS-based formation flying will become commonplace. Very low cost scientific payloads, such as Spartan, will be deployed from Space Station, fly in formation, and autonomously return for eventual retrieval. In the future, aerobots, autonomous balloon systems flying in formation using GPS-like navigation sensing will be performing high precision, 3-D Mars mapping in preparation

Projected Launch Year	Mission Name	Mission Type
00	New Millennium Program (NMP) EO-1	Earth Science
01	Gravity Recovery and Climate Recovery (GRACE)	Earth Science
02	University Nanosats/Air Force Research Laboratory Launch 1	Technology Demonstrator
02	University Nanosats/Air Force Research Laboratory Launch 2	Technology Demonstrator
02	Auroral Multiscale Mission (AMM)/APL (MIDEX)	Space Science/SEC
03	Techsat-21/AFRL	Technology Demo
03	New Millennium Program (NMP) ST-5	Space Science
04	DARPA/AF Discoverer II	Technology Demo
05	New Millennium Program (NMP) ST-3	Space Science/ASO
05	Magnetospheric Multiscale (MMS)	Space Science/SEC
05	Space Interferometry Mission (SIM)	Space Science/ASO
07	Global Precipitation Mission (EOS-9)	Earth Science
07	Geospace Electrodynamics Connections (GEC)	Space Science/SEC
08	Constellation-X	Space Science/SEU
08	Magnetospheric Constellation (MC)	Space Science/SEC
08	Laser Interferometric Space Antenna (LISA)	Space Science/SEU
09	DARWIN Space Infrared Interferometer/European Space Agency	Space Science
10	Leonardo (GSFC)	Earth Science
11	Terrestrial Planet Finder	Space Science/ASO
	Astronomical Low Frequency Array (ALFA)/Explorers	Space Science
05+	Soil Moisture and Ocean Salinity Observing Mission (EX-4)	Earth Science
05+	Time-Dependent Gravity Field Mapping Mission (EX-5)	Earth Science
05+	Vegetation Recovery Mission (EX-6)	Earth Science
05+	Cold Land Processes Research Mission (EX-7)	Earth Science
05++	Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)	Space Science/SEU
15+	MAXIM X-ray Interferometry Mission	Space Science/SEU
15+	Solar Flotilla, IHC, OHRM, OHRI, ITM, IMC, DSB Con	Space Science/SEC
15+	NASA Goddard Space Flight Center Earth Sciences Vision	Earth Science
15+	NASA Institute of Advanced Concepts/Very Large Optics for the Study	Space Science
15+	NASA Institute of Advanced Concepts /Ultra-high Throughput X-Ray	Space Science
15+	NASA Institute of Advanced Concepts /Structureless Extremely Large Yet Very Lightweight Swarm Array Space Telescope	Space Science

Notes: ASO-Astronomical Search for Origins, SEC-Sun Earth Connections, SSE-Solar System

for human exploration and conducting scientific investigations around the planet.

It is clear that formation flying will usher in fundamental change and a new era in science data collection in space. The mission sets already on the drawing boards at NASA and the DoD span the spectrum of formation flying performance requirements, from 2-3 spacecraft in a loose formation to tens or hundreds of tightly controlled spacecraft flying in an armada. Some missions, such as the Magnetospheric Constellation (MAGCON) will require very loose (1-100 km) formation knowledge and control. On the other end of the spectrum, space science gravity sensing missions, interferometry missions, planet finders and relativity missions will require micro-meter and, in some cases, pico-meter knowledge and nanometer control. These differing mission sets require an entire spectrum of sensing, controlling and actuation capabilities to satisfy these varied requirements challenges.

Developing the technology to produce virtual platforms and sensor webs is a long-range challenge. Similar to most complex technology development programs [BAUE98], there are several technological “stairsteps” that must be overcome to go from autonomous navigation and constellation control to multi-vehicle relative navigation and finally to virtual platforms and sensor webs. Figure 1 depicts the planned evolution of distributed spacecraft technology from its current state to the goal of virtual platforms and sensor webs. Precisely, a virtual platform is defined as the collective, coordinated operation of multiple spacecraft that are oriented and positioned to achieve pre-defined mission objectives. A sensor web is a collection of science instruments operating collectively to gather data or co-observe. The sensors may be on spacecraft, sciencecraft, balloons, Unmanned Aerial Vehicles (UAV), etc.

A distinction must be made between formation flying and constellation control. NASA is focusing on the control of multiple, cooperating satellites in autonomous formations that operate together to accomplish a variety of science objectives. Therefore, formation flying typically involves active, real-time, closed-loop relative-navigation and control of these satellites in the formation. Sensor webs can also be characterized as formations of multiple assets; that is, space vehicles, sub-orbital balloons and surface robots, all operating autonomously, but collectively. Constellation control typically does not require this level of autonomy or real-time coordination. However, several subsystems, such as the satellite cross-link communications and data transfer are critical to all variations, constellations, formations and webs.

Converting this formation flying vision into a real product is a formidable task, and both NASA and the Air Force are leading several government-academia-contractor teams to make this happen. Some of the leading researchers that comprise this team are from the Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), AFRL, the Naval Research Laboratory (NRL), the Johns Hopkins University Applied Physics Laboratory (APL), Stanford University, Massachusetts Institute of Technology (MIT), University of California Los Angeles, AI Solutions and Space Products and Applications (SPA), Incorporated.

NASA’s primary focus for formation flying technology is through the “Distributed Spacecraft” Thrust Area (TA) of the Cross Enterprise Technology Development Program (CETDP). The research within this thrust area is focused on the collaborative behavior of multiple space vehicles, forming a distributed network of individual vehicles acting as a single functional unit while exhibiting a common system-wide capability to accomplish various mission goals. A combined government-university-industry team has identified six formation flying technology focus areas that require further research to reach the goals of future missions. These technology focus areas include:

- A. Sensor development (where am I?)
- B. Actuator development (how I can get to where I want to be?)
- C. Telecommunications—inter-spacecraft communication (where is the rest of the fleet?)
- D. Formation Control Strategies (where should I be?)
- E. Computing and Data Management, and (how do I get where I want to be?)
- F. Tools & Testbeds

The development and deployment of robust sensing systems (focus A) to determine absolute and relative navigation is critical to enable autonomous formation flying. These sensor systems are being modified for ranging and to also transmit formation control data to the virtual platform or sensor web—providing a telecommunications capability (focus C) for the formation or web. Embedded in these transceivers and in the discrete formation space vehicles are the computers (focus E) and the autonomous formation control

algorithms (focus D) that process the sensor data and issue formation control commands to the fleet. The vehicle actuators (focus B) then reposition and reorient (attitude & navigation) the vehicles in the formation based on the above control commands to achieve the mission requirements.

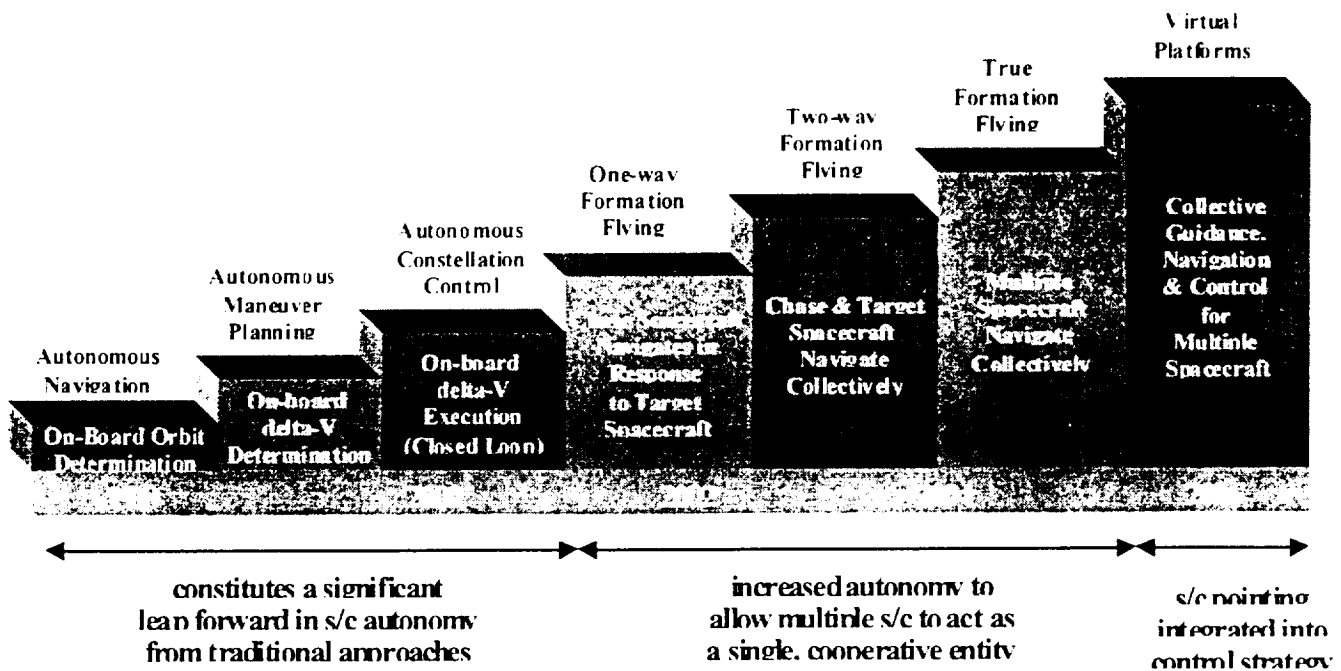


Fig. 1

Developing and validating the performance and capabilities of these new formation flying technologies will be very challenging. Thus a complement of tools in concert with ground and on-orbit testbeds (focus F) are being created to minimize risk and reduce research costs. The rest of this paper describes these six focus areas in more detail, including the current status of each of these and the future directions.

2-FOCUS AREA A: SENSORS

The ability to determine and control the relative positions, orientations, and their respective velocities for a vehicle or fleet of vehicles is only as effective as the sensors that are on-board these vehicles. To this end, the formation flying team is emphasizing the development of new relative and absolute sensing techniques.

Spaceborne GPS—For near Earth formation flying, the capstone position and timing sensor technology is spaceborne GPS. Several teams, including NASA GSFC, APL, and JPL, are working with university and industry partners to move this technology to the forefront [BAUE98].

PiVoT – NASA/GSFC's Guidance, Navigation and Control Center (GNCC) is developing a GPS receiver called Position, Velocity and Time (PiVoT). PiVoT, based on the Mitel semiconductor chipset, is designed to insert into a PCI backplane, supports four antennae, has a microcontroller that off-loads processor demand, and can be interfaced to any microprocessor on the PCI bus. This allows the PiVoT to be portable to RISC processors such as the StrongArm and full instruction set microprocessors from Motorola, Intel, etc. PiVoT is an open architecture design, allowing the users to check their own tracking loops and code. The receiver board has numerous radiation hardened and tolerant parts, with the limiting parts being the Mitel chipset. GSFC has performed radiation testing of the chipset and found it to be reliable to 20K RADs without any shielding. PiVoT is compact and light weight. The power requirement will be determined by the user-selected microprocessor, but a custom power supply with latchup protection provides the power. Typically, the GPS portion of the receiver consumes approximately 4 – 6 watts. Currently, two units are undergoing testing and are successfully tracking satellites via the antennae in the laboratory environment.

VISNAV—Many formation flying missions, in particular, interferometry missions, rely on high precision relative position and attitude knowledge. Although GPS can provide this capability near Earth,

deep space missions must rely on other technologies. One of these alternative technologies is vision-based navigation (VISNAV) under development by Texas A&M University. VISNAV comprises an optical sensor of a new kind combined with specific light sources (beacons) in order to achieve a selective or "intelligent" vision.

Attitude Sensing—If formation flying technologists are going to achieve the virtual platforms goal, a set of absolute and relative attitude sensing devices are needed. Very precise, autonomous star tracking and gyro systems are needed to support the requirements demanded from formation flying missions such as the interferometry missions. In addition, developing fleets of very low cost spacecraft will require inexpensive, miniaturized attitude sensors such as Micro-Electro-Mechanical Systems (MEMS) gyros, and low weight, low power attitude tracking devices. To this end, the CETDP Distributed Spacecraft TA has teamed with the Micro/Nano Sciencecraft TA to ensure these sensors are available for formation flying missions of the future.

3-FOCUS AREA B: ACTUATORS

The ability to redirect specific spacecraft as well as entire formations in translation and rotation is contingent upon the installation of adequately sized attitude and trajectory actuators. From an attitude perspective, these are usually reaction wheels and thrusters. From a trajectory perspective, these are primarily thrusters. Formation control puts high demands on these spacecraft actuators. New technologies are necessary to ensure sufficient resources are available onboard to maintain the formation. These technologies must support higher pointing constraints, provide greater precision thrust capability, provide lower noise or disturbance and significantly reduce use of expendables.

Several initiatives are underway to develop actuators that enable very low cost formation flying. This activity is sponsored by both the Distributed Spacecraft and the Micro/Nano thrust areas in NASA and by AFRL's TechSat 21 program. Of particular interest are micro-reaction wheels and micro-thrusters. These support small micro and nanosatellites as well as extremely fine pointing required for formation flying. In NASA, micro-thruster research is being conducted at GSFC in the GNCC to support future formation flying testbeds such as the University Nanosats and Orion. At AFRL as at GSFC, a great deal of effort is being spent on MEMS, pulse plasma and colloid thrusters.

NASA/GSFC is sponsoring the development of a Pulse Plasma Thruster (PPT) as an experimental technology for the NMP EO-1. The PPT uses solid Teflon propellant and is capable of delivering high specific impulse (900-1200 s), very low impulse bits (10-1000uN-s) at low average power (<1 to 100W).

Colloid microthrusters (with thrust in the milli-Newton range) are a promising new technology in the field of small spacecraft propulsion. Because of their small size and low weight these devices are particularly interesting to missions incorporating formation flying and nanosatellites. Colloid thrusters work by accelerating charge particles using an electrostatic field. Current research, based at the Stanford Plasma Dynamics Laboratory (PDL), aims to better understand the working mechanism of colloid thrusters, and to develop an integrated, micro-electro-mechanically based colloid thruster for space propulsion.

4-FOCUS AREA C: TELECOMMUNICATIONS

Formation Flying cannot be accomplished without an adequate inter-spacecraft communications medium. The specific medium used for formation flying spacecraft is primarily a function of the performance and science data gathering requirements for the mission. Missions requiring low to medium formation knowledge and control (km to cm-level) and nominal data requirements will use Radio Frequency (RF) based telecommunications capabilities. Currently, researchers are investigating GPS-like transceivers as the primary RF-based formation flying communications medium. Missions requiring high performance formation knowledge and control (sub-cm to picometer) and/or very high data rates (>10 Mbps) will require optical communications methods to support the virtual platform.



APL CLT—JHU/APL Cross Link Transceiver (CLT) represents an integrated crosslink communication and relative navigation system for multiple distributed spacecraft flying in formation. [STA 99]. The CLT (figure 3) will support inter-spacecraft communications at a nominal rate of 5-300kbps focused primarily upon the distribution of command and control information. A critical aspect of the CLT crosslink communications approach is that it is explicitly designed to support formation flying

missions, which require capabilities such as dynamic adaptivity, scalability, and robustness. As such, the CLT is designed to simultaneously receive data from multiple spacecraft and the signal structure is such that it will support a variety of logical command and control architectures (e.g., centralized, hierarchical, fully distributed) by providing a flexible communications infrastructure. The CLT provides both an absolute and relative navigation solution (position and velocity) and provides precision time recovery and a steered one pulse-per-second output.

JPL AFF—The NMP ST-3 mission is expected to demonstrate various elements of the technology required for space interferometry, including the Autonomous Formation Flying (AFF) sensor [LAU 96], and an autonomous reconfigurable formation control system [WANG 96, HADA 97].

SPTC—The Stanford Pseudolite Transceiver Crosslink (SPTC) is being developed at Stanford as a relative navigation and communication crosslink system for formation flying spacecraft. The SPTC was designed with COTS devices (modems, L_1 pseudolites, and an attitude-capable GPS receiver). Carrier phase Differential GPS (CDGPS) measurements are used to achieve very precise relative positioning. Using GPS measurements, the SPTC is expected to provide relative position accuracies on the order of 3-8 cm, depending on GPS satellite geometry. Attitude determination to within 0.25 degrees [CORA 99].

ITT LPT—NASA/GSFC and ITT are jointly sponsoring the development of a Low Power Transceiver (LPT). The LPT integrates TDRSS S-band 2-way communications and GPS navigation in a compact flexible package. Once completed, the LPT provides substantial reductions in power, size, weight, and cost, and is envisioned to serve as the communications/navigation subsystem for a wide range of space-based science missions. This technology is ideal for formation flying which requires crosslink communications and relative navigation often on small spacecraft with limited power.

GSFC OMNI – The NASA/GSFC Operating Missions as a Node on the Internet (OMNI) program is looking at the protocol end of the communication problem. By using TCP/IP protocols, the OMNI group leverages off the extensive commercial technology development to create a robust spacecraft-to-ground and spacecraft-to-spacecraft communications infrastructure. In such a scenario a formation of spacecraft could operate as its own intranet in space. The OMNI group has tested ping, NTP and FTP with the University of Surrey's UOSAT 13 spacecraft in a ground to space scenario.

JPL Optical Communications—At NASA, the Jet Propulsion Laboratory is conducting research in optical communications systems. These systems will provide a significant crosslink and downlink conduit for scientific and formation control data. Moreover, these laser-based systems can also provide very precise information on the relative positioning and orientation of multiple spacecraft in a formation (micrometers and arc-seconds). Using these optical and metrology systems, a “virtual aperture” can be developed using several spacecraft in a tight formation.

5-FOCUS AREA D: FORMATION CONTROL STRATEGIES

Implementation of distributed coordinating satellite concepts requires tight maintenance and control of the relative distances and orientations of the participating satellites. Thus formation control poses very stringent challenges in the areas of:

1. Onboard sensing of relative and absolute vehicle positions/attitudes,
2. Activity planning and scheduling including maneuvering, retargeting, collision avoidance, and aperture optimization while tracking resource/task allocation within the fleet,
3. Modeling the orbital mechanics and the impact of differential drag and solar disturbances,
4. Fleet and vehicle autonomy, including high-level and distributed fault detection and recovery,
5. Decentralized control & computation for a fleet of many (e.g. from six to hundreds) vehicles,
6. Testbeds and simulations to validate the various sensing and control concepts.

A ground-based command and control system for relative spacecraft positioning would be complex, heavily over-burdened, and not sufficiently rapid for corrective control. Thus, the focus is to significantly increase the onboard autonomy of the future spacecraft, thereby reducing the ground support required.

Conceptually, autonomous formation flying is a process in which an array of spacecraft makes continuous measurements of the “array configuration” and uses these measurements to maintain an existing configuration or to smoothly transition to a new one, all without external measurement or control. Generally speaking, the array configuration includes both the distances between spacecraft in the array and

the orientations of the spacecraft in a coordinate frame defined by the array's internal geometry. From initialization to targeting, then to maneuvering, the formation will experience significant changes in control requirements. A completely autonomous, configurable control system must be implemented to switch between the various system models and controllers.

Cooperative formation control can take several forms. Typically, for a small number of spacecraft (e.g. less than six) operating as a formation, a master/slave or a hierarchical control structure could be used. In the master/slave scenario, a single spacecraft acts as a leader and issues commands to the fleet or the fleet reacts to the actions of the leader according to a planned behavior. The hierarchical control divides the formation into subsets. Each subset has its own leader and a small number of "followers." However, for large formations, these types of control carry too much overhead and are impractical. Decentralized architectures are non-hierarchical and coordination by a central supervisor is not required. Detected failures would then tend to degrade the system performance gracefully. Each node in the decentralized network processes only its own measurement data in parallel with all of the others.

One simple decentralized approach is the "nearest neighbor" approach where the overall formation is maintained as a side effect of communicating only with those elements in the formation that are closest, and maintaining relative geometry to them. This approach supports large formation, where complete communication is not practical due to distances or occultations.

A more advanced example of the decentralized approach being pursued by NASA/GSFC uses a stand-alone, standard GPS point solution to maintain the spacecraft formation [CARP 99]. In this approach, if each of the vehicles transmits and receives data to and from the other vehicles in the formation, relative states can be computed, without the need for direct measurements of the inter-satellite states. This would enhance the accuracy and allow coordination of the formation maneuvers. If sufficient onboard processor capacity is available, the GPS measurement data (e.g. pseudo-range, carrier) could be processed for improved accuracy. Ideally, if one or more of the vehicles had the capability to make relative measurements to the other formation members, all available data could be used to maximize the relative navigation accuracy.

Several other groups are working on resolving the various technical issues discussed above. A group at the University of Texas A&M has developed an optimal relative orbit design for minimizing the effects of the dominant orbital perturbations (using the nonlinear orbital dynamics) [SCH 99]. They have also developed techniques to perform fuel optimal control of a two spacecraft rendezvous [VAD 99].

6-FOCUS AREA E: COMPUTING AND DATA MANAGEMENT

Computing and data management presents a number of challenges both in the hardware and algorithmic areas. Groups at GSFC, JPL, Ames, AFRL, ACADEMIA and industry are addressing many of these.

Very high performance, low-power, computing devices are critical for formation flying, sensor webs and nanosatellites. The sophistication of the formation control algorithms and the need for sufficient floating point computing power for formation flying demand high performance microprocessors. These devices must be radiation and single event effect tolerant since they are mission critical. Often the processor will be on micro and nanosatellites or spacecraft that are small, have little surface area for solar arrays, and are power poor. Leveraging off the commercial sector, NASA, AFRL and the commercial space industry are working feverishly to bring these devices to flight-worthy status. Devices such as the StrongARM, 603e and 720 Power PC and the RAD6000 represent the current generation of spaceflight processors.

A great deal of effort is being spent on spacecraft automation and autonomy. First, some definitions are necessary. Automation is focused on ground control while autonomy is on-board processing. Automation usually involves scripting product generation and creating a "lights-out" environment or situation where flight engineers are paged when necessary. The real focus of this work is to reduce mission cost. The goals of autonomy, on the other hand, are to create "thinking" spacecraft that can operate independent of ground support. Autonomy is truly critical in the realm of formation flying.

NASA/Ames has developed a remote agent for autonomous spacecraft planning and scheduling. This tool was first successfully tested on DS-1. Now it is being adapted to apply to distributed spacecraft. The technology will be combined with GSFC's decentralized control, and used to efficiently control a formation or sensor web autonomously.

The introduction of autonomous systems, however, creates its own problems. The nondeterministic nature of autonomy greatly complicates testing. New techniques and tools are necessary to determine and fully understand system behavior. It is no longer possible to use structured testing and try to cover all the "expected" paths or outcomes.

Another area of study is fault detection and correction. This can be particularly critical in a distributed control environment. To ensure graceful degradation of the formation, failures must be detected and managed. For example, some of the distributed spacecraft control techniques at GSFC are looking at voting schemes and decentralized fault detection to determine and remove failing spacecraft.

With large numbers of spacecraft collecting potentially huge amounts of data, serious research into data management and reduction is necessary. In some formations or mission concepts, the data must be shared between spacecraft, and allowances must be made for these large communication bandwidths. Also, the spacecraft will need to determine what data should be sent to the ground, what can be thrown away, and what needs to be kept on board in case the ground requests it or further processing is necessary. Aging of the data must also be managed. These are just a few of the problems to be solved.

7-FOCUS AREA F: TOOLS & TESTBEDS

The challenge of deploying distributed spacecraft systems lies not only in controlling the vehicles to achieve and maintain a specified formation, but also in distributing information among the vehicles so that they act as a coordinated system. This requires the development of advanced distributed spacecraft control architectures and algorithms, absolute and relative navigation and attitude sensors, inter-spacecraft communication systems, and information management systems. To minimize mission risk associated as these new technologies are infused into formation flying missions, testbeds that will enable comprehensive simulation and experimentation are required.

NASA/GSFC GNCC has developed a multi-pronged approach to testbed development. The first prong of this effort is a series of small testbeds based on specific technologies. For example, the team at GSFC has developed a GPS testbed that includes GPS constellation RF simulators and flight ready receivers. See Figure 4. A second prong includes incorporating these smaller testbeds into a ground-based Formation Flying Testbed (FFTB). This testbed takes advantage of a COTS product called VirtualSat Pro. VirtualSat, developed by the Hammers Co., is a real-time spacecraft dynamic simulator capable of simulating a formation of spacecraft. It was developed to facilitate flight software development and testing in parallel with hardware development, including hardware-in-the-loop testing. Since VirtualSat has a component structure, software simulation modules are replaced by hardware as it is developed. These smaller hardware-based testbeds can, therefore, be plugged into the FFTB to create an extensive end-to-end flight simulation environment.



Figure 4: GPS Test Facility

The third prong in the GSFC testbed strategy is an extensive on-orbit campaign of demonstration missions. These demonstrations will validate numerous formation flying technologies, including those mentioned in this paper, in flight experiments.

NASA/GSFC is not the only group developing formation flying testbeds. Testbeds are under development or in use at JPL, AFRL, MIT and Stanford. The goal, where possible, is to link these testbeds using the internet to further support distributed spacecraft technology development.

EO-1 Enhanced Formation Flying Experiment—The primary objective of the enhanced formation flying experiment on the EO-1 mission is to demonstrate onboard autonomous navigation and formation flying control between the EO-1 and Landsat-7 spacecraft. An automated mission design and automated maneuver

planning tool, AutoCon [BAUE 97], which was developed by AI Solutions under direction of a GSFC GNCC team, has been used for operational mission design. AutoCon has been modified to operate onboard the spacecraft to enable autonomous formation flying. To accomplish this the flight control system plans a maneuver that places EO-1 within one minute of separation from Landsat-7 and then maintain that separation to a tight tolerance of six seconds for an extended period of time. Flight validation is currently scheduled for September 2000.

Orion—The Orion mission was developed to demonstrate true formation flying in low earth orbit using very low cost microsatellites designed and built at Stanford University. See Figure 6. This mission will validate several key sensing and control issues associated with formation flying, and it represents an important step towards the virtual platforms envisioned for future Earth Sciences Enterprise missions.

The microsatellite design for this mission is based on a modified version of a low-cost, low-weight spacecraft bus developed at Stanford called SQUIRT. Apart from being an excellent testbed for demonstrating the overall design of an active microsatellite, there are four important technical objectives:

- On-orbit demonstration of formation control.
- Demonstration of a low-cost, low-power GPS receiver for real-time attitude & relative navigation and control. The particular emphasis of the program is on CDGPS for very precise relative navigation.
- Demonstration of a real-time inter-vehicle communication link to support the CDGPS and control data.
- Investigate several configurations of the fleet to demonstrate the formation flying in fuel-optimized relative orientations.

The original mission plan had 3 Orion vehicles launched together, initialized, and perform a sequence of coarse and precise formation flying. This has recently been changed so that a single Orion vehicle would fly in formation with two Emerald vehicles that are being developed at Stanford and Santa Clara Universities as part of the AFRL Nanosat program. While the Emerald vehicles are less capable than the current Orion spacecraft design (they have no significant thrust actuation and significantly reduced onboard computing) this fleet of three vehicles should be able to meet all of the original Orion formation flying sensing and control objectives.

ST-3—Space Technology (ST)-3 is being developed by JPL and Ball Aerospace to demonstrate spaceborne optical interferometry with very large baselines (100m-10km). This can be accomplished using multiple spacecraft flying in precise formation. While the optical pathlengths over these distances must be controlled to nanometers, the vehicle accuracies are 1 cm and 1 arcmin in relative range and attitude, respectively. The mission will also be used to test the new relative ranging technology, AFF, and various formation control algorithms.

ST-3 consists of two spacecraft, operating as a master/slave formation. Both spacecraft comprise a single instrument and are constrained to move together in a relative distance of 50-1000 meters. To meet mission goals, the control system must maintain the distances between spacecraft to within 2 cm, and the relative orientations of the spacecraft within 1 arcminute per axis. The sensing for ST-3 will be performed using the AFF described previously. Both spacecraft will be collecting elements for the interferometer. Each will use a mirror with a diameter of 12 cm to reflect the collected light to one of the spacecraft that will also serve as the combiner. During a planned lifetime of six months, the instrument will demonstrate its ability to point at specified targets, change baseline length, and maintain the formation at the required accuracy, as well as to find and track the interferometric fringes and report its measurements back to Earth.

University Nanosats— DoD, NASA, and Industry are sponsoring the development and launch of 8 nanosatellites (approximately 10 kg) to demonstrate miniature bus and distributed spacecraft technologies. This University Nanosat program, with two launches schedule in 2002, will serve as a technology host to test formation control algorithms, software and hardware in the space environment. Various technologies can be tested and validated in parallel on each formation. The parallel development of these spacecraft, as well as Orion, provides opportunities to “climb the technology stair steps” while minimizing mission risks through multiple on-orbit tests.

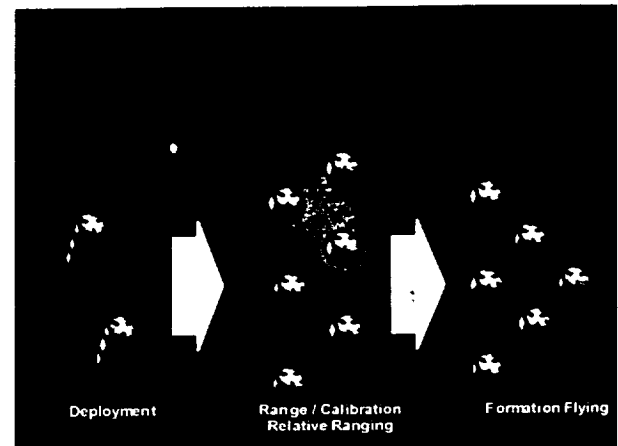


Figure 6: Orion—True Formation Flying

The Universities have teamed up to create three formations. A team from Arizona State University, University of Colorado Boulder, and New Mexico State University is developing the Three Corner Sat Constellation. The primary science objective of the Three Corner Sat constellation is to perform stereo imaging. To accomplish this objective, the 3 satellites will form a "virtual formation" in which the satellites cooperate to perform targeting, data acquisition, and data downlinking. A team from Utah State University, University of Washington, and Virginia Polytechnic Institute & State University are developing the Ionospheric Observation Nanosatellite Formation (ION-F) to demonstrate satellite coordination and management technologies. The primary objective of the mission is to investigate the ionosphere (Density Structure Sizes, Drifts, Decay Rates) using measurements from the distributed satellites. Propulsion, crosslink and formation control algorithms are being investigated for this mission. A team from Stanford Space Systems Development Laboratory, Santa Clara Remote Extreme Environment Mechanisms Laboratory, and the Stanford Formation Flying Laboratory is developing Emerald. Emerald is being designed as a low-cost demonstration of the basic components of NASA's "virtual spacecraft bus." In particular, it will demonstrate the use of Carrier-Phase Differential GPS (CDGPS) techniques to autonomously track the relative position and attitude between several spacecraft.

TechSat-21—AFRL is leading the development of microsatellites (10--100kg) to replace several complex, expensive Air Force satellites, such as MilStar, Defense Support Program, and Defense Meteorological Satellite Program. The key focus of this work is to develop new technologies, such as MEMS, that will lead to lightweight, low-cost, and highly capable microsatellites. The AFRL is exploring this new paradigm for performing space missions in an effort called TechSat-21 (Technology Satellite of the 21st Century). A space-based radar mission for Ground Moving Target Indication was chosen as a stressing case and is the focus of the initial investigation. The program is focused on MEMS development, sparse aperture design, propulsion and formation control strategies.

8-CONCLUSIONS

Formation Flying technology will make fundamental changes in the way the Civil and DoD space community conducts missions in space. These changes will revolutionize all space missions of the future: Earth Science, Space Science, Human Exploration and DoD and Commercial ventures. The NASA/AFRL Formation Flying team is on the forefront of the Formation Flying technology effort, providing hardware and software solutions to overcome the current technology hurdles. A series of collaborative on-orbit experiments and ground-based tools and testbeds will provide a low cost validation of the Formation Flying hardware and software algorithms. Future missions will rely heavily on advance control techniques and spaceborne autonomy to enable the construction of Virtual Platforms in space.

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